Cloud-Aerosol-Radiation Ensemble Modeling System (**CAR**):

One application on aerosol climate effects

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  - CWRF/CAR on-line experiments
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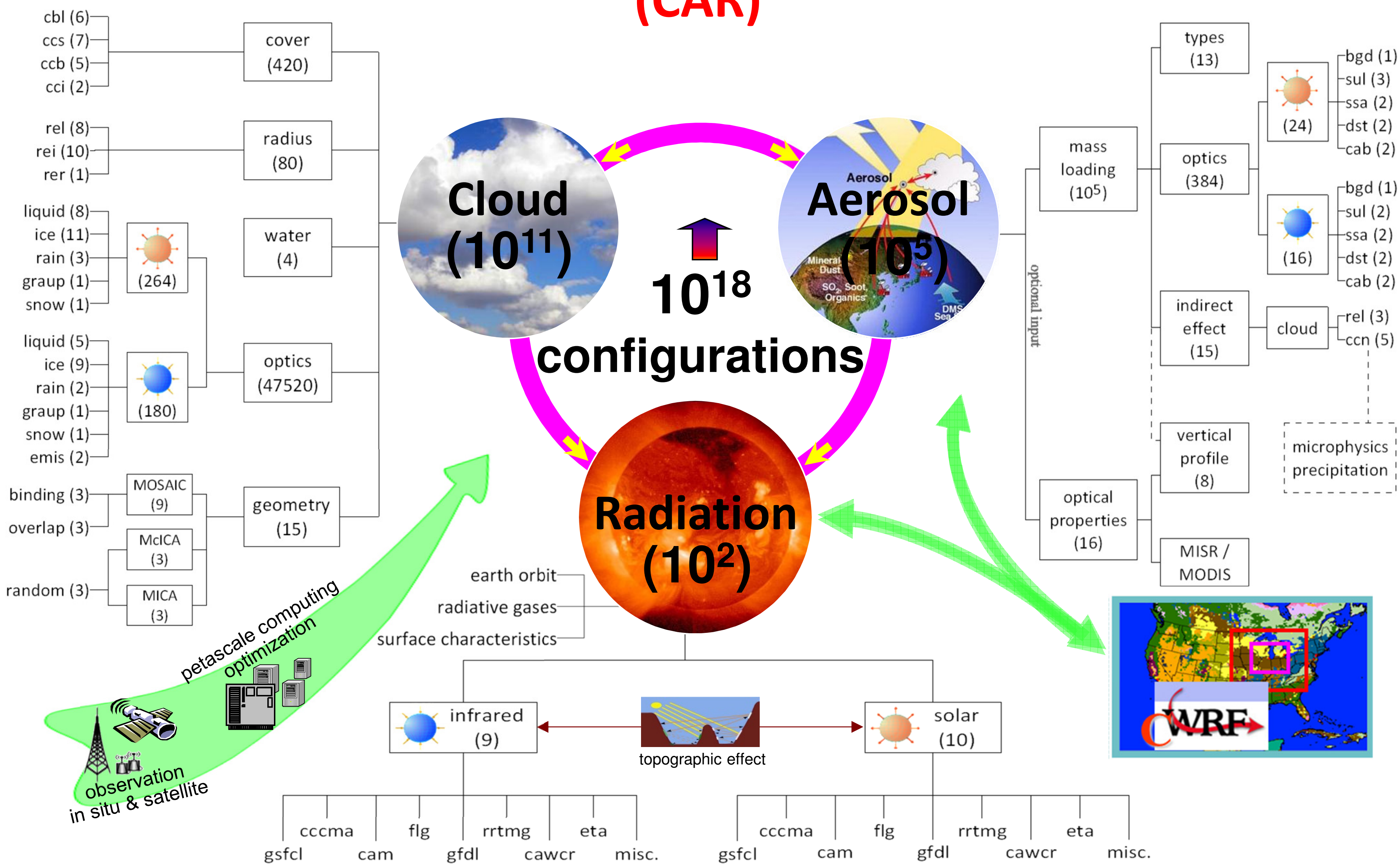
Motivation

As well known, **how to more realistically describe cloud-aerosol-radiation interactions and their feedbacks** is the most challenging problem in the development of climate models. The large uncertainty in cloud-aerosol-radiation interactions is the main factor causing the large diversity of climate sensitivities among different climate models (IPCC, 2007). A basic problem is **the lack of a systematic estimate of the uncertainties among cloud/aerosol/radiation schemes**.

So:

- **To collect the most schemes commonly available in the modeling community.**
- **To separate cloud, aerosol, and radiation transfer.**
  - Cloud cover, water path, effective size/radius, vertical profiles, optical properties
  - Aerosol loadings, effective size, optical properties
  - Radiation transfer
- **To explicitly treat the radiative effects of cloud including cloud vertical overlap and aerosol including aerosol 1st indirect effects.**
- **To consistently apply external factors across radiation transfer codes.**
  - Solar insolation / Earth orbit variations
  - Gas concentration / Aerosol loading
  - Surface albedo / Surface emissivity
- **To make all alternative schemes fully exchangeable and selectable.**
- **To provide huge platform on cloud-aerosol-radiation schemes for optimized physics ensemble.**

Cloud-Aerosol-Radiation Ensemble Modeling System (CAR)



More details on http://car.umd.edu

Table 1. Average **percentage differences of SWDNS** from LBL reference calculations (LBLRTM and CHARTS) among 7 CAR major radiation schemes with different cloud optical property schemes for CIRC Phase-I case 6 [%]. **Values in red are the smallest errors. Yellow shadings are the original schemes used for each radiation code.**

radiation codes	gsfcl	cccma	cam	flg	gfdl	rrtmg	cawcr
case 6 (thick cloud case)							
swl1	-11.66	7.22	-11.94	-8.87	-4.87	-9.97	-16.02
swl2	-2.47	18.08	-2.84	**0.60**	4.37	-2.47	-8.47
swl3	-12.75	5.70	-11.86	-8.63	-6.15	-11.38	-17.11
swl4	**-0.83**	19.33	**-1.96**	1.31	6.53	**-0.52**	**-4.35**
swl5	-4.49	14.98	-4.15	-0.76	2.36	-3.27	-9.57
swl6	-2.47	18.08	-2.84	**0.60**	3.93	-2.47	-8.47
swl7	-6.13	13.40	-5.14	-4.91	**1.97**	-5.49	-9.10
swl8	-15.33	**4.27**	-15.18	-15.48	-8.26	-16.79	-18.60

8 CAR SW cloud Liquid optical property schemes (swl):

swl1: Fu and Liou (1992); swl2: Chou et al. (1999)

swl3: Dobbie et al. (1999); Lindner and Li (2000)

swl4: Hu and Stanmes (1993) look-up tables

swl5: Kiehl et al. (1996); swl6: Chou et al. (1999)

swl7: Slingo (1989); swl8: Hu and Stanmes (1993)

CIRC phase I case 6: 3/17/2000 (SGP), thick cloud, cwp = 263.4g m^{-2}

CIRC: NASA Continual Intercomparison of Radiation Codes

http://circ.gsfc.nasa.gov

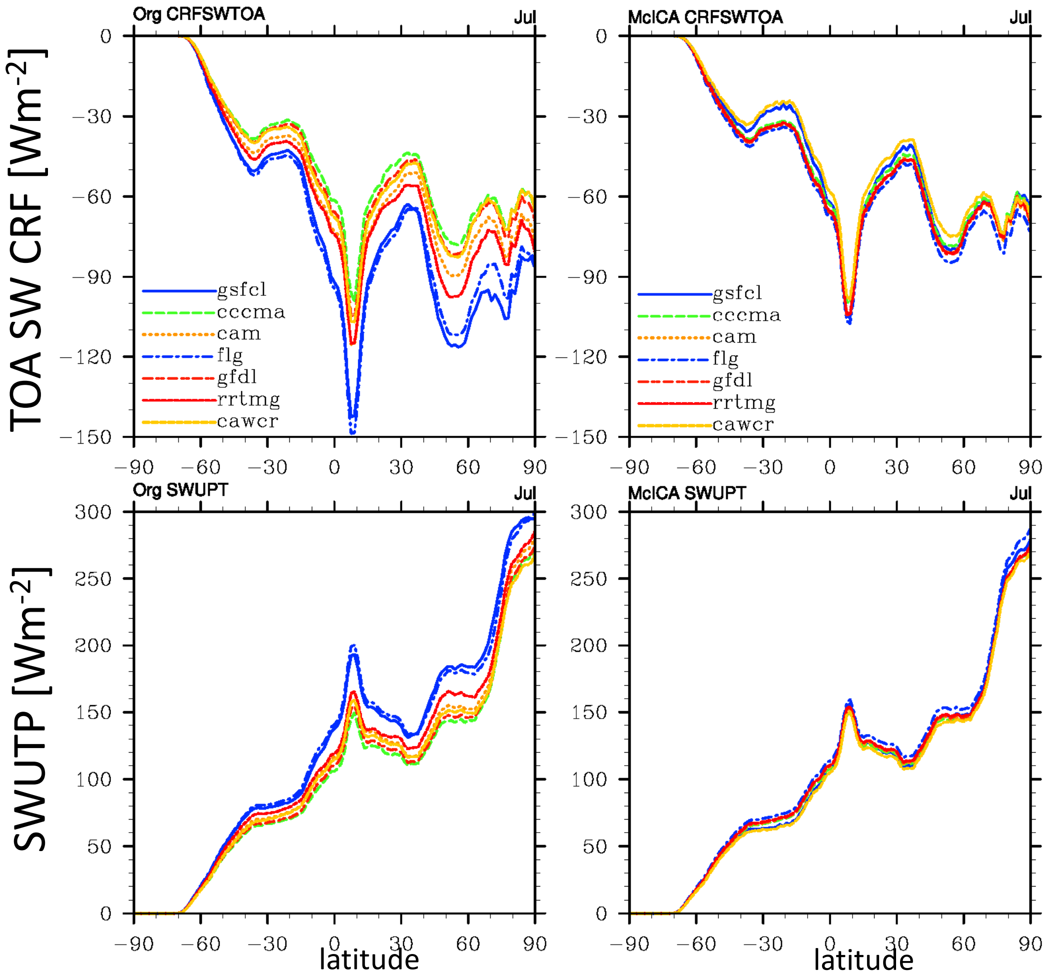
The CAR system discloses:

- The strong dependence of one radiation transfer code on the selective schemes for cloud optical property.

- The strong dependence of the performance of one cloud optical property scheme on the selective radiation transfer schemes.

Above implies that the conclusions about cloud-aerosol-radiation interaction uncertainties reached by using one radiation transfer scheme even with several options for cloud optical property is hard to be applied to other radiation transfer schemes.

Obviously CAR depicts the quite comprehensive numerical representation for the nonlinear interactions among cloud, aerosol, and radiation. The CAR definitely has superior to any single radiation package to describe the numerical representations of cloud-aerosol-radiation interactions.



July zonal mean TOA SW CRFs (top) and SWUPT (bottom) from standalone CAR tests driven by ECWMF interim 2004 global data (Uppala et al. 2008).

Org (left): the original build-in cloud vertical overlap schemes

(maximum/random)

McICA (right): McICA treatment

(Independent Column)

(Barker et al. 2002; Pincus et al. 2003; Räisänen et al. 2004)

The CAR is a powerful tool for comparisons among different radiation transfer codes, different cloud.

Strikingly, when McICA treatment is consistently applied to each of radiation code, the min-max range among CAR 7 major radiation schemes for both SWUPT and TOA SW CRF largely decrease, e.g., over tropical area, from about 60 Wm^{-2} to about 10 Wm^{-2} or less. So the same cloud profiles, due to McICA treatments consistently applied, largely reduce the differences of radiative fluxes and SW CRFs among 7 different radiation transfer codes, **indicating the quite large dependence of one radiation transfer scheme on the cloud vertical overlap treatments.**

How to reduce the CAR (10^{18}) to a reasonable size?

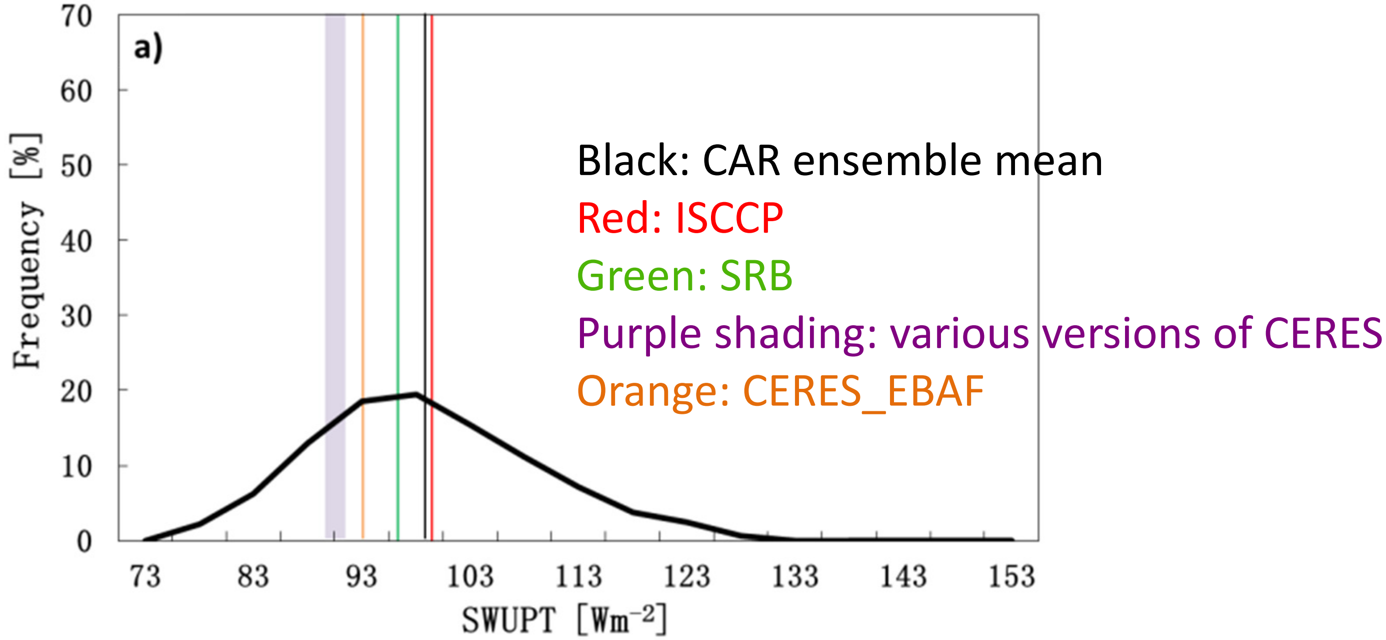
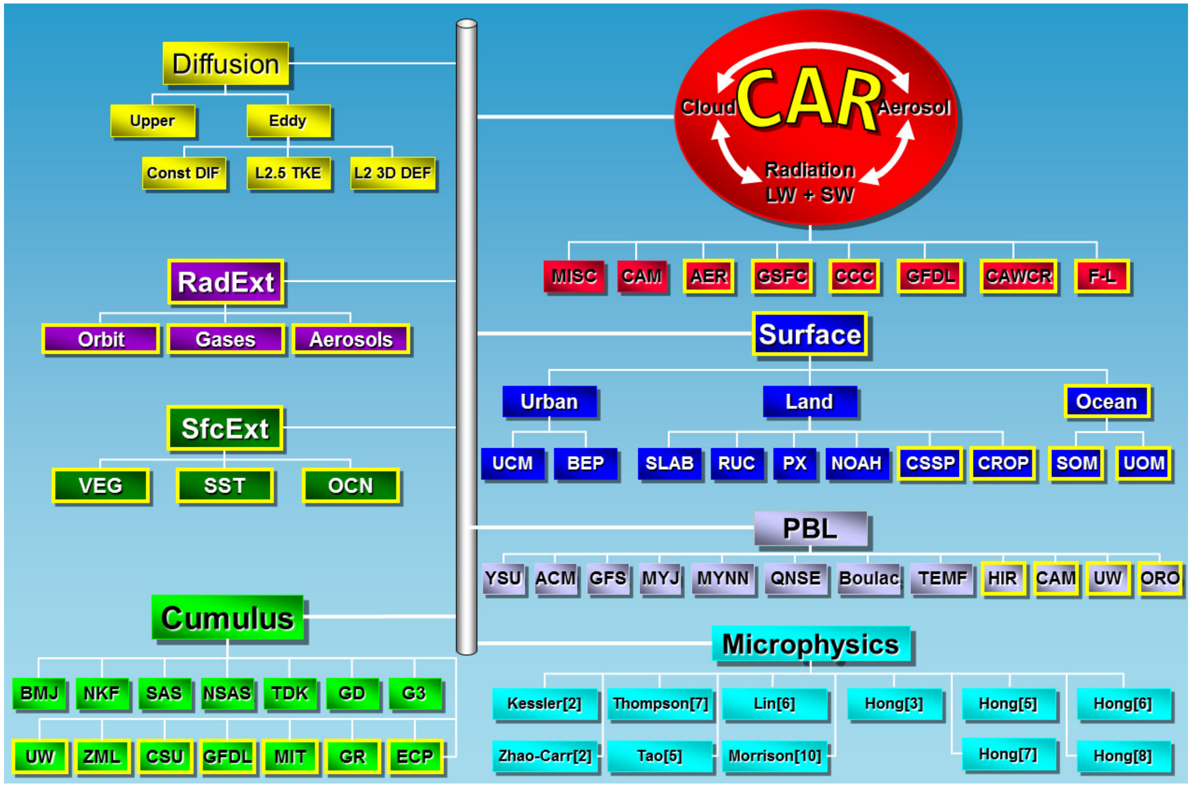


Figure The member frequency distributions (*black curves*) of domain-mean SWUPT (W.m^{-2}) over [60^{o}S, 60^{o}N] for a subset of 448 CAR members. They are driven by ERA interim data for July 2004.

In near future, we will try more CAR members to locate the CAR ensemble mean in the middle of the observation ranges, and then those CAR members located in the accepted ranges compared with observations will be chosen to form the base for later studies on cloud-aerosol-radiation interactions. By doing so, the CAR size will be reduced to about 1000 ~ 2000, even less dependent on different research purpose.

CWRF/CAR



- **CWRF is a Climate extension of the Weather Research and Forecasting model (WRF):**

  Inherits all WRF functionalities for NWP while enhancing the capability to predict climate, thus has unified applications for both weather forecast and climate prediction.

- **CWRF incorporates a grand ensemble of alternative physics schemes:**

  Contains more than 10^{24} of alternative physics configurations representing interactions between surface (land, ocean), planetary boundary layer, cumulus (deep, shallow), microphysics, cloud, aerosol, and radiation.

  Facilitates the use of an optimized physics ensemble approach to improve weather forecast or climate prediction along with a reliable uncertainty estimate.

  Weights individual members by their skills resolving past observations to provide strong constraints on the ensemble prediction of future outcome.

- **CWRF provides a societal service capability for climate impacts:**

  Meets the actual need of stakeholders for credible information on natural resource changes at regional-local scales.

  Couples the predictive ability for terrestrial hydrology, coastal ocean, UV radiation, crop growth, air quality, water quality, ecosystem.

More details on http://cwrf.umd.edu

Experiments design:

The influences of the following factors on aerosol direct effects and 1st indirect effects have been studied:

- ✓ **CAR cloud scheme combinations**
- ✓ **cloud vertical overlap treatments**
- ✓ **radiation transfer codes**
- ✓ **cloud droplet number (CDN) schemes**
- ✓ **aerosol optical property schemes**

3 different experiment sets are conducted:

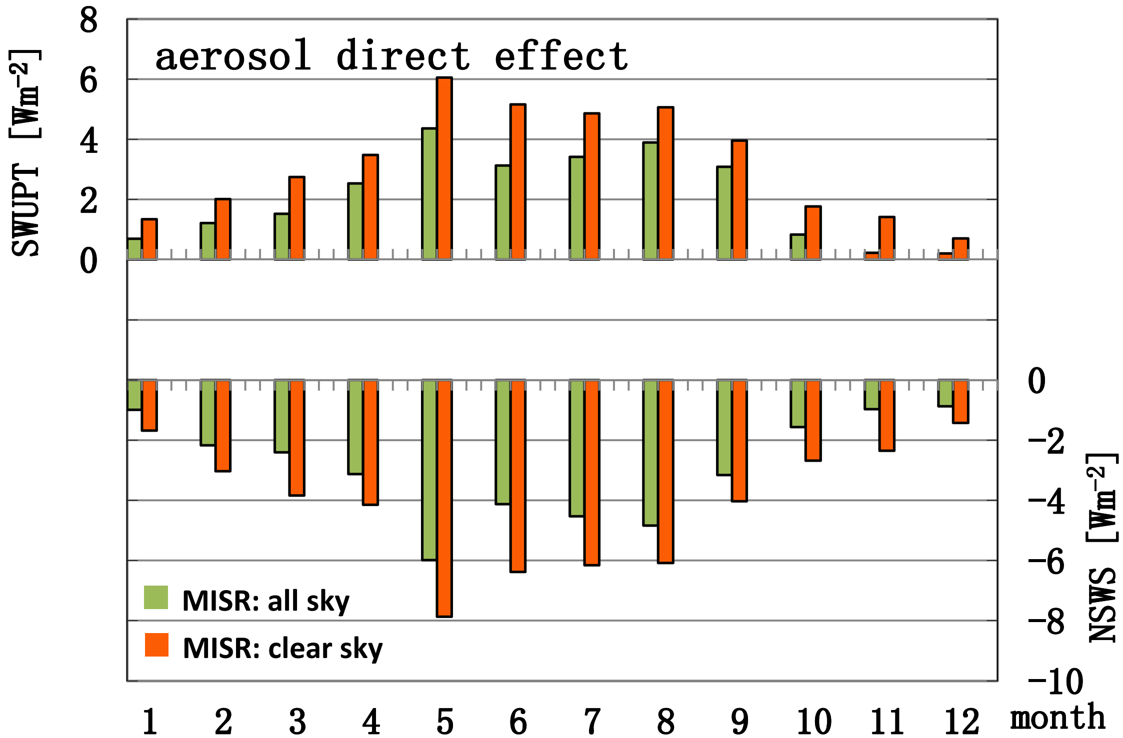
- **CRM cases**: standalone CAR tests driven by 2000 CRM integration based on the field measurements over the ARM/SGP (97.5°W, 36.6°N) for 2000 whole year (Wu et al. 2007). The time resolution = 15min, total 34944 time steps for 2000.

- **ERI cases**: standalone CAR tests driven by ECWMF Interim 2004 global data (Uppala et al. 2008).

- **CWRF cases**: online CWRF/CAR sensitivity experiments driven by ECWMF Interim 2004 data.

Monthly mean results shown here.

- Aerosol direct effects
  - Standalone CAR experiments
  - CWRF/CAR on-line experiments



Monthly mean aerosol direct effects on SWUPT (TOA upward SW radiative fluxes) and NSWS (SFC net SW radiative fluxes) by using MISR aerosol loadings.

Here only show the means among 7 major CAR-radiation schemes: gsfcl, cccma, cam, flg, gfdl, rrtmg, cawcr.

Red : clear-sky
Green : all-sky

CRM cases

Under cloudy conditions, the aerosol direct effects become smaller than those under clear sky,

For example, in June, SWUPT:

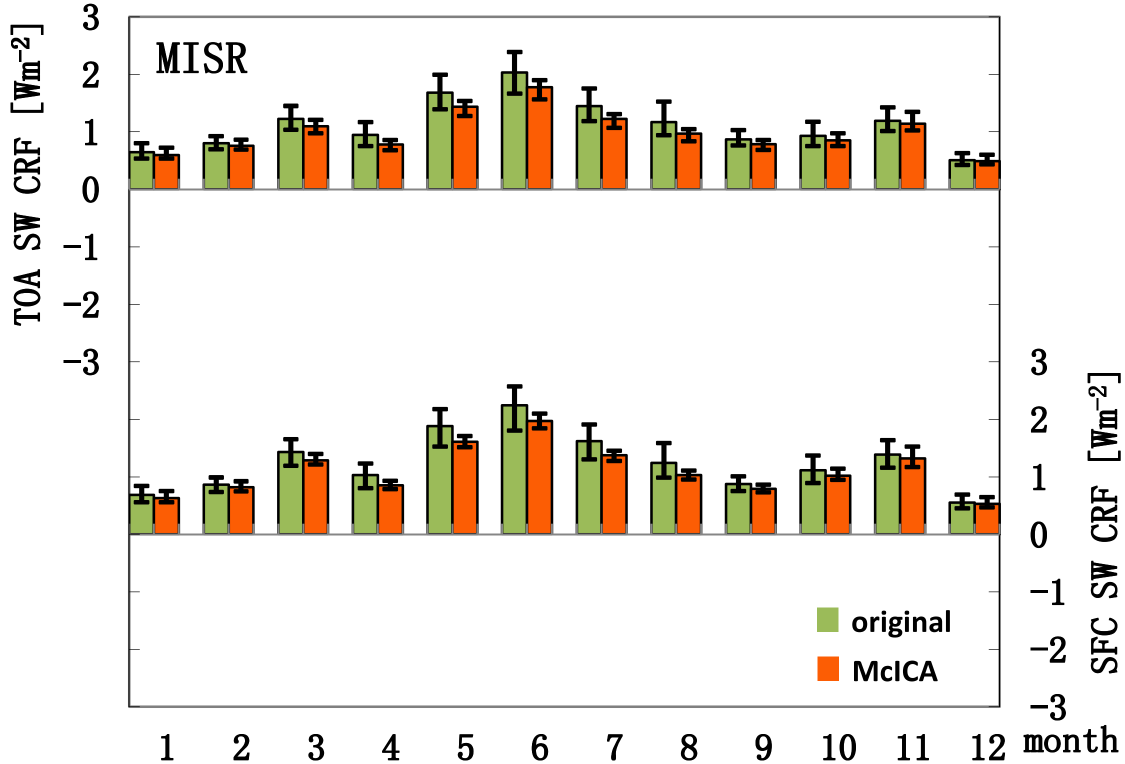
for all sky: ~3.1 Wm^{-2} ; for clear sky: ~5.2 Wm^{-2}; the difference: ~ 2.1 Wm^{-2}

Aerosol and cloud influence each other.

On one side, cloud decrease aerosol direct effects.

On the other side, aerosol direct effects cause cloud radiative forcing (CRF) to change.

Comparisons among radiation codes and cloud vertical profiles



CRM cases

Monthly mean aerosol direct effects on Cloud Radiative Forcings (CRF) by using **MISR** Aerosol loading.

Color bars: means
Error bars: min-max ranges among 7 major CAR-radiation schemes

Red bars: original cloud vertical overlap
Green bars: McICA cloud treatment

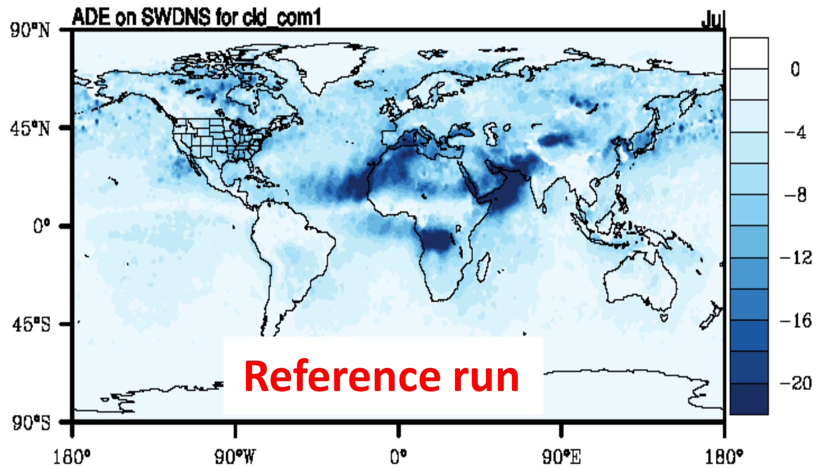
1. Clearly aerosol direct effects do cause changes of CRFs with ranges about 0.5~2.5 W.m^{-2}. And the overall positive signals indicate that aerosol direct effects decrease cloud radiative forcings. **Undoubtedly cloud and aerosol interact with each other.**

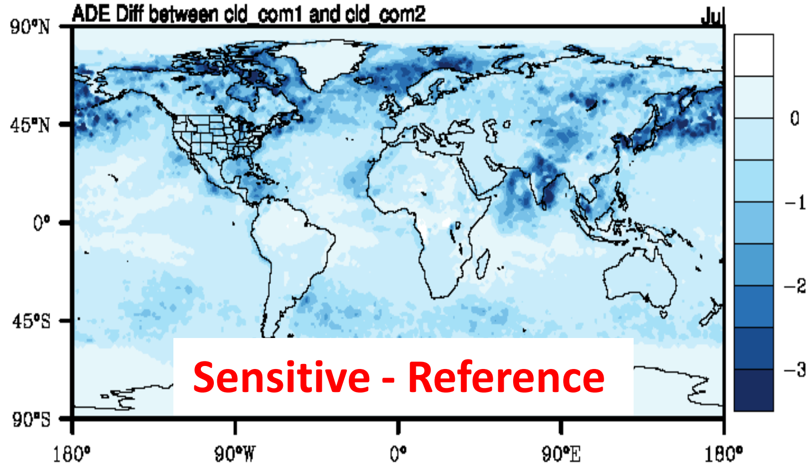
2. The obvious min-max ranges with values about 0.2~0.7 Wm^{-2} from original cloud vertical overlap schemes (green) show the clear differences among different radiation schemes.

3. From McICA cloud treatments (red), the min-max range reducing to about 0.2~0.3 Wm^{-2} indicates that the same cloud profiles, due to McICA treatments consistently applied, largely reduce the CRF differences caused by aerosol direct effects among different radiation transfer codes. **So cloud vertical overlap schemes play obvious effects on aerosol direct effects.**

e.g., according to CRFs about 2 Wm^{-2}, the change from 0.7 to 0.3 Wm^{-2} in July is quite large, i.e., about 20%.

Comparisons among cloud scheme combinations





ERI offline case

(Radiation: gsfcl, MISR aero loading)

Monthly mean aerosol direct effects (ADE) on **SWDNS** for July 2004.

Here two cloud scheme combinations:

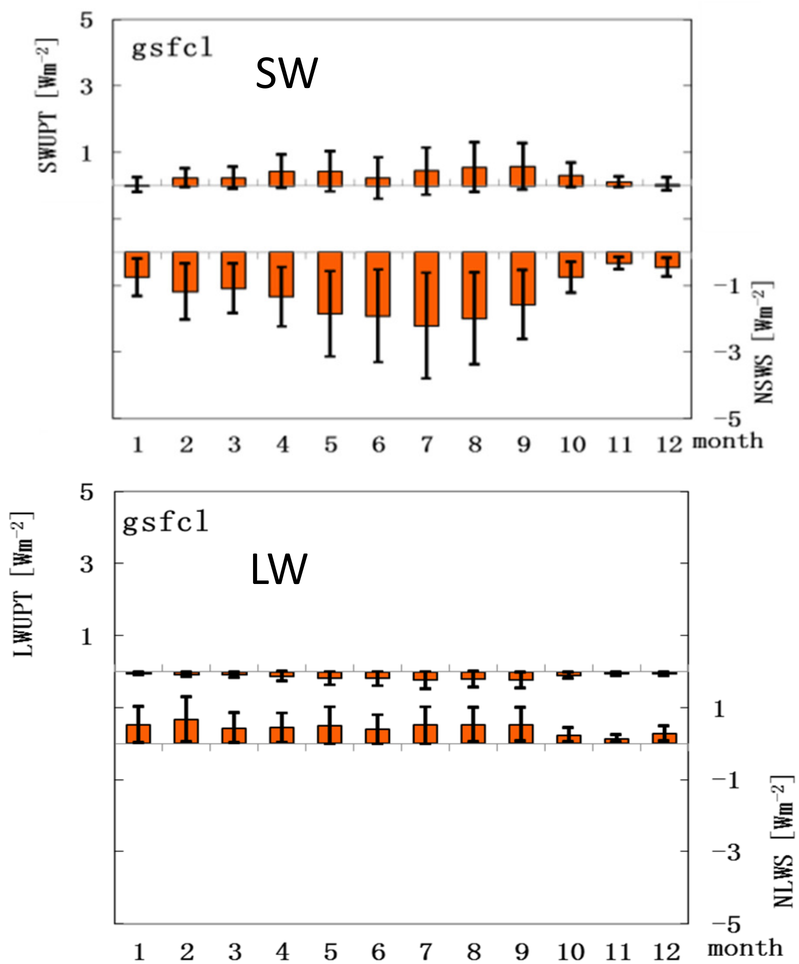
cld_com1: ccs1 (Xu and Randall 1996), ccb3 (Slingo 1987), dei2 (Sun and Rikus 1999), swi106 (Fu et al. 1998)

cld_com2: ccs2 (Slingo 1987), ccb5 (Ferrier et al. 2002), dei7 (from GFDL), swi401 (Ebert and Curry 1992).

and swl6 (Chou et al. 1999) and rel1 (Savijärvi et al. 1997) for both.

Through comparisons, clearly that generally over those regions with small aerosol direct effects, quite large differences of aerosol direct effects between different cloud scheme combinations can be found, and over those regions with strong aerosol direct effects, those differences of ADE between different cloud scheme combinations are always small. **This indicates that cloud properties do influence aerosol direct effects, especially over the areas with small aerosol direct effects.**

Comparisons among aerosol SW/LW optical schemes



CRM cases

Monthly mean aerosol direct effects on SWUPT, NSWS, LWUPT and NLWS by using 2000 **CMIP5** recommended aerosol mass loading.

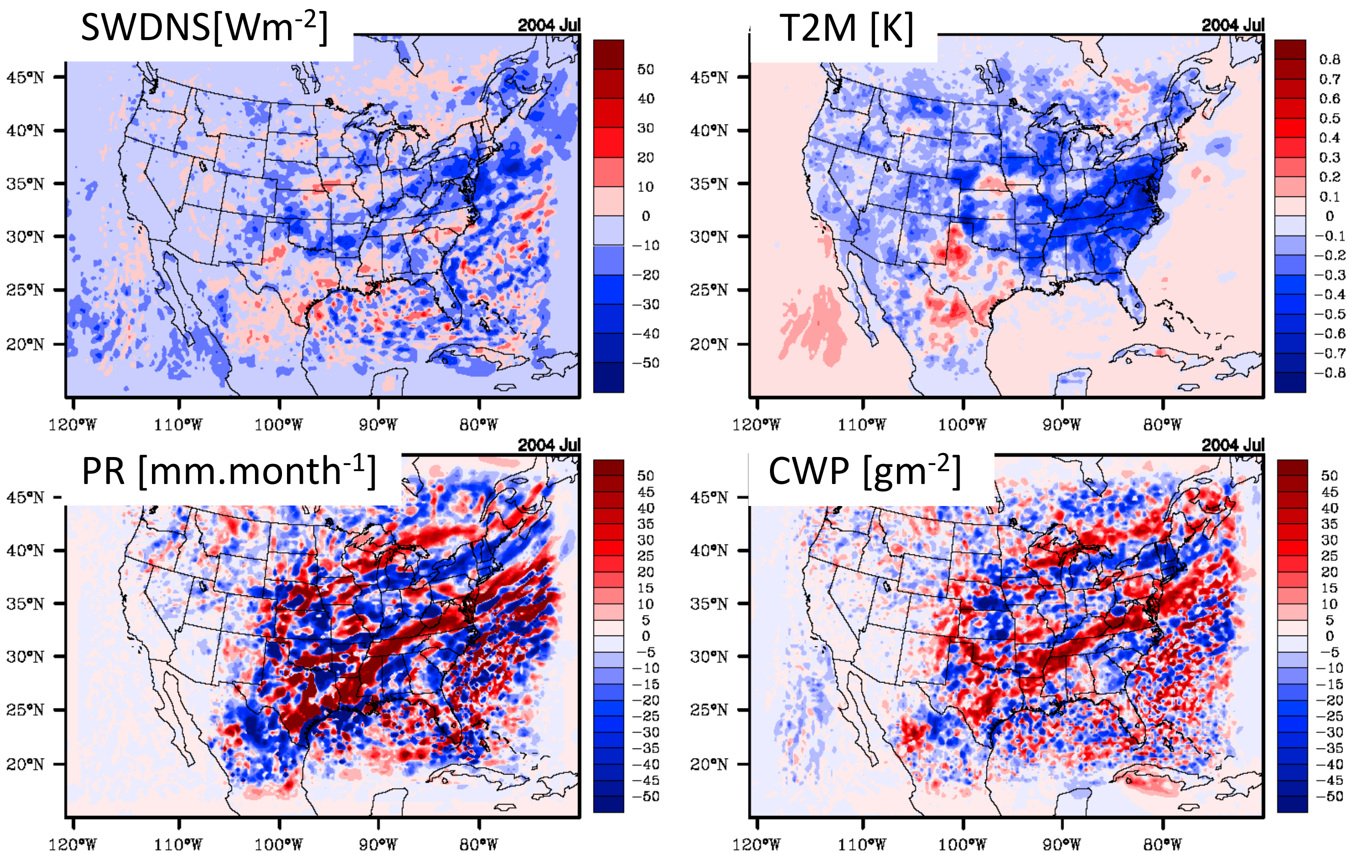
color bars and error bars are respectively the means and **standard deviation** among **24** CAR-aerosol optical scheme combinations **for SW, and** among **16** CAR aerosol optical scheme combinations **for LW**.

GSFCL

The standard deviations, with values about 0.2 ~ 0.7 Wm^{-2} for SWUPT and about 0.2~1.6 Wm^{-2} for NSWS, are quite large, especially for May to September, indicating that **different aerosol SW optical scheme combinations generate quite different aerosol direct effects even with the same aerosol mass loading.**

For LW, the similar results can be obtained.

CWRF: aerosol direct effects



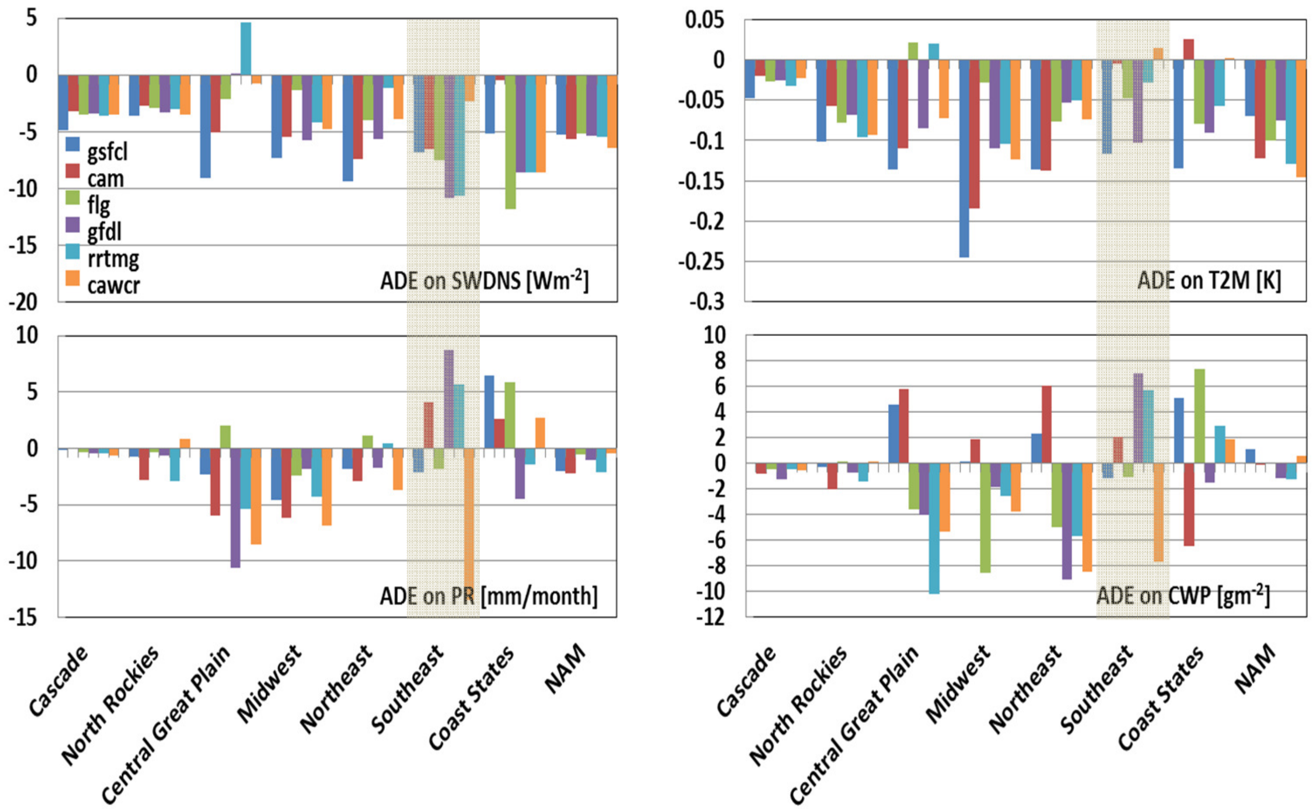
CWRF cases gsfcl

July monthly mean aerosol direct effects on SWDNS, T2M, PR, and CWP by using MISR aerosol for 2004.

Clearly shown by CWRF/CAR, aerosol has quite large direct effects on SWDNS, T2M, PR, and CWP over USA domain, especially over the Southeast parts of USA.

For example, **the magnitudes of the changes of SWDNS are about 10~30Wm^{-2};**
the changes of T2M can be > 0.5K;
the changes of PR can reach to > 50 mm/month, which assumes the similar pattern as those for the changes of total CWP.

CWRF: comparisons among radiation schemes



CWRF cases

Monthly mean **aerosol direct effects** on

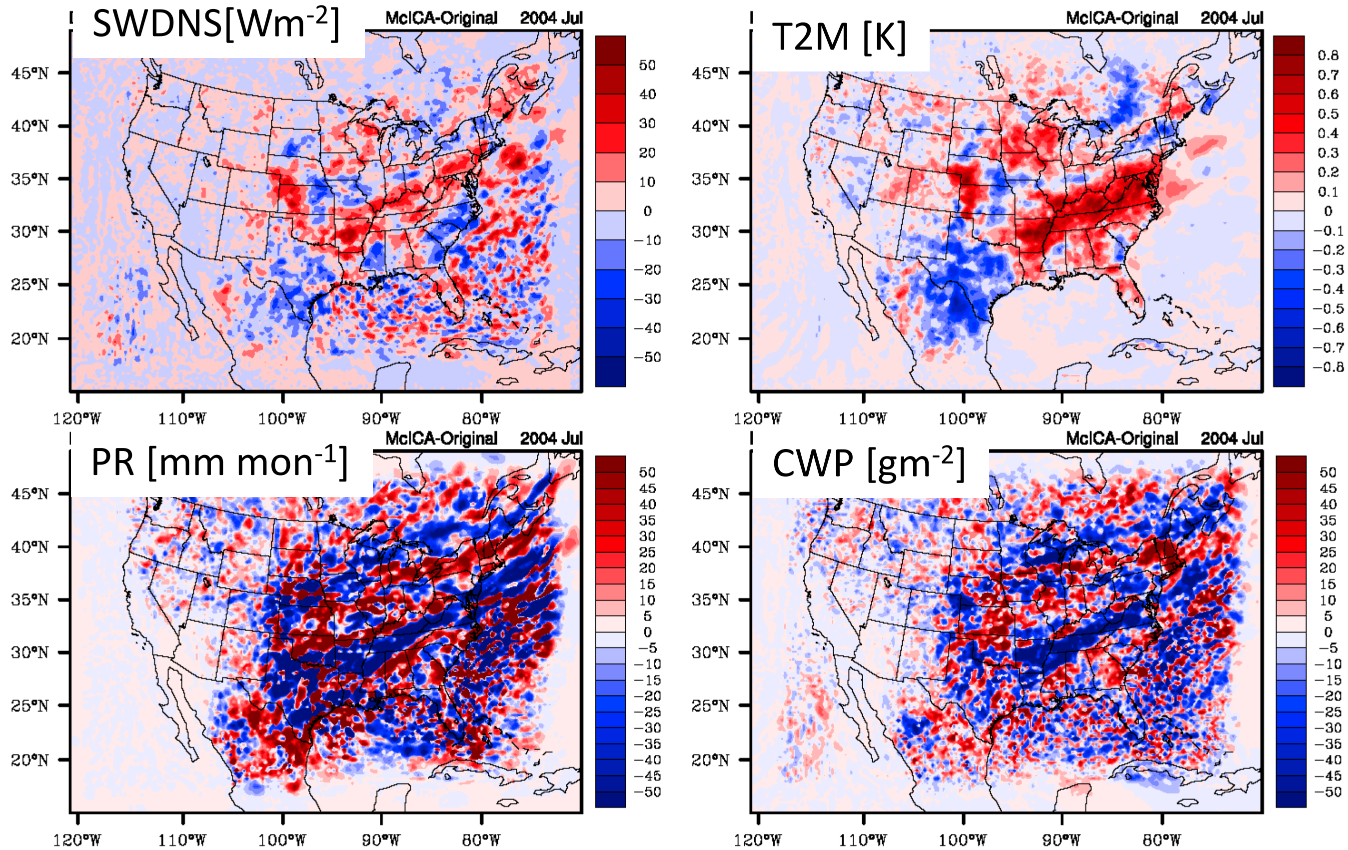
SWDNS[Wm^{-2}]	T2M [K]
PR [$mm.month^{-1}$]	CWP [gm^{-2}]

over 8 US domain by using MISR aerosol for July 2004.

Clearly cloud feedbacks are different with different radiation transfer schemes applied in CWRF, e.g., over Southeast, cawcr largely decrease CWP, gsfcl and flg slightly decrease CWP, while cam, gfdl and rrtmg increase CWP. So with different cloud feedbacks, the changes on air surface temperature caused by aerosol direct effects are obviously different: so for cawcr, T2m increase is reasonable.

Obviously Different radiation transfer codes generate quite different aerosol direct effects in regional climate model.

CWRF: comparisons among cloud vertical profiles



CWRF cases gsfcl

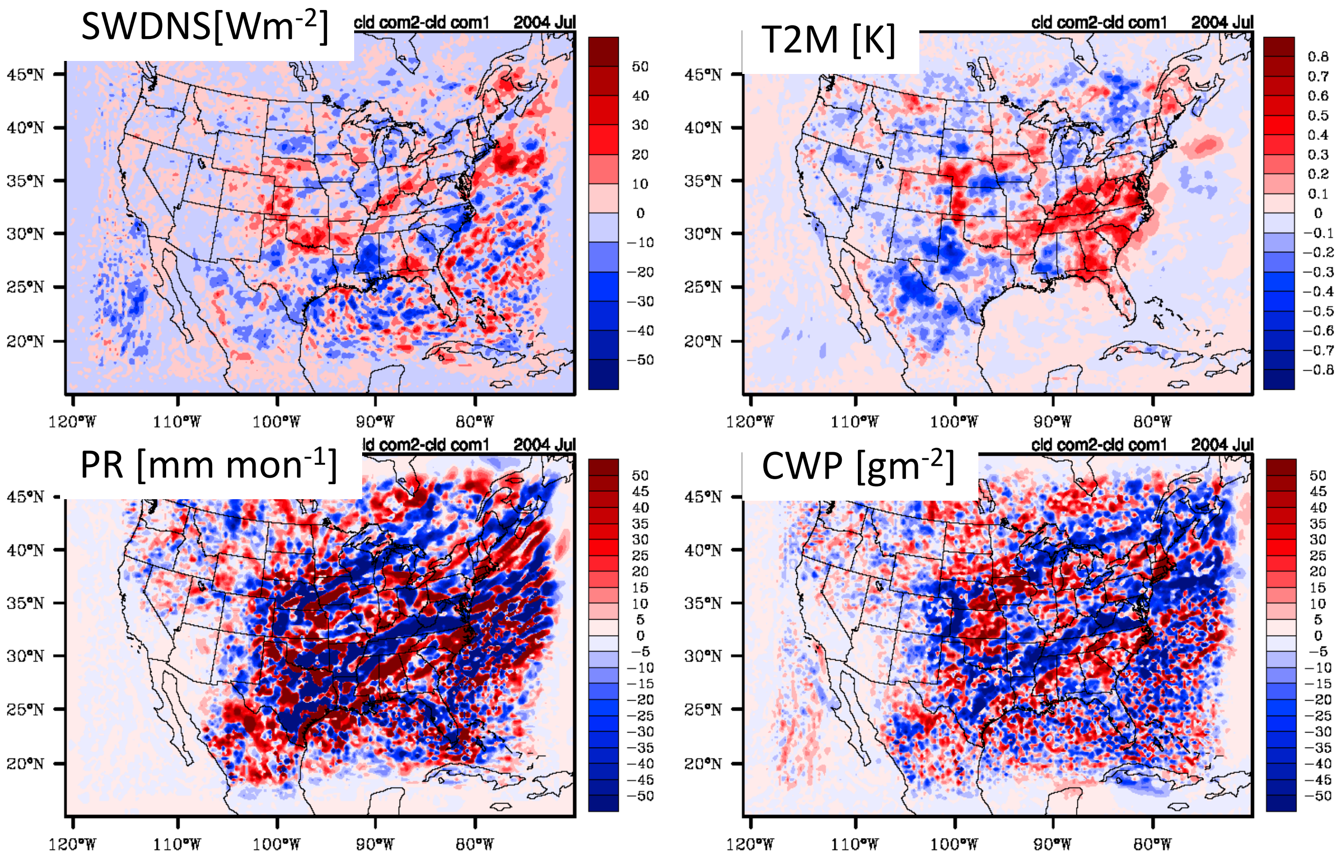
The differences of monthly mean aerosol direct effects on SWDNS, T2M, PR, CWP between **McICA treatment** and **Original cloud vertical overlap scheme** by using MISR aerosol for July 2004.

McICA-Original

Clearly different cloud vertical overlap treatments have quite different influence on aerosol direct effects.

e.g., over Southeast of USA, the magnitudes of the changes of SWDNS are about 10~30Wm^{-2};
the changes of T2M can be >0.5K;
the changes of PR can reach to > 50 mm/month, which assumes the similar pattern as those for the changes of total CWP.

CWRF: comparisons among cloud scheme combinations



CWRF cases gsfcl

The differences of monthly mean **aerosol direct effects** on

SWDNS[Wm^{-2}]	T2M [K]
PR [$mm.month^{-1}$]	CWP [gm^{-2}]

between **two CAR cloud components** by using MISR aerosol for July 2004.

Cld_com2 – cld_com1

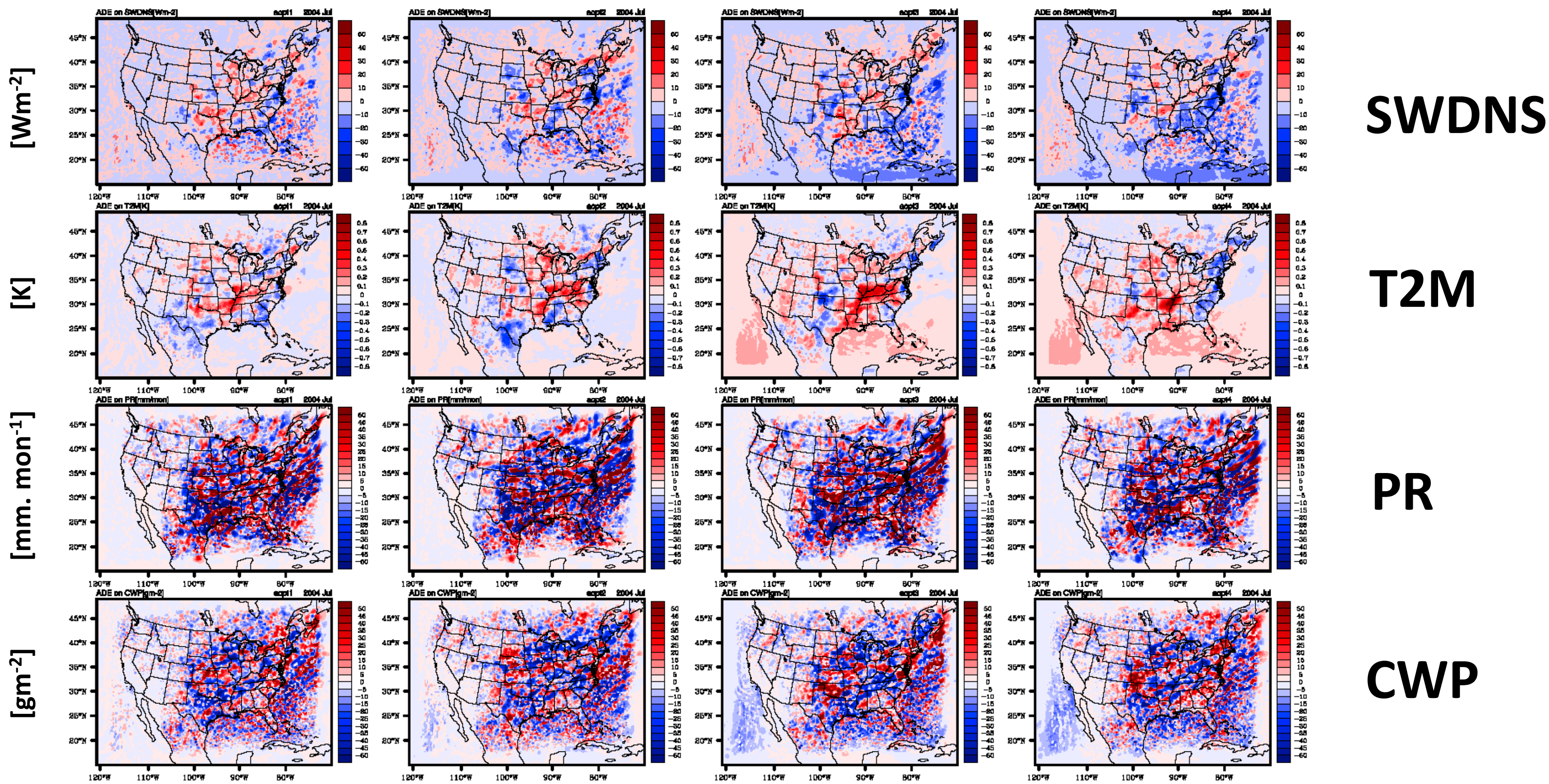
cld_com1: ccs1 (Xu and Randall 1996), ccb3 (Slingo 1987), dei2 (Sun and Rikus 1999), swi106 (Fu et al. 1998)
cld_com2: ccs2 (Slingo 1987), ccb5 (Ferrier et al. 2002), dei7 (from GFDL), swi401 (Ebert and Curry 1992).
and swl6 (Chou et al. 1999) and rel1 (Savijärvi et al. 1997) for both cld_coms.

Clearly different CAR cloud scheme combinations perform different influence on aerosol direct effects.

e.g., over Southeast of USA, the changes of SWDNS are about 10~20Wm^{-2};
the changes of T2M can be about 0.5K;
the changes of PR can reach to > 50 mm/month, which assumes the similar pattern as those for the changes of total CWP.

CWRF: comparisons among aerosol optical scheme combinations

gsfcl with McICA



aopt1	**aopt2**	**aopt3**	**aopt4**
aop1_sw/aop1_lw	**aop3_sw/aop2_lw**	**aop7_sw/aop3_lw**	**aop9_sw+aop10_lw**

Monthly mean **aerosol direct effects** on SWDNS [Wm^{-2}], T2M [K], PR [$mm.month^{-1}$], and CWP [gm^{-2}] **for 4 CAR aerosol optical scheme combinations** by using **CMIP5 recommended data** for July 2004.

Clearly different CAR aerosol optical scheme combinations perform different influence on aerosol direct effects.

aop1_sw:

Li et al. (2001) for sulfate, sea salt,
and dust + Baümer et al. (2007) for carbon;

aop3_sw:

Kiehl and Briegleb (1993) for Sulfate
Li et al. (2001) for sea salt and dust
Baümer et al. (2007) for carbon

aop7_sw:

Li et al. (2001) for sulfate and sea salt
Gu et al. (2006) for dust
Baümer et al. (2007) for carbon

aop9_sw:

Kiehl and Briegleb (1993) for Sulfate
Gu et al. (2006) for dust
Li et al. (2001) for sea salt
Baümer et al. (2007) for carbon

aop1_lw:

Li et al. (2001) and Li and Min 2002 for sulfate, sea salt and dust
Baümer et al. (2007) for carbon

aop2_lw:

Li et al. (2001) and Li and Min 2002 for sulfate and dust
Gu et al. (2006) for sea salt
Baümer et al. (2007) for carbon

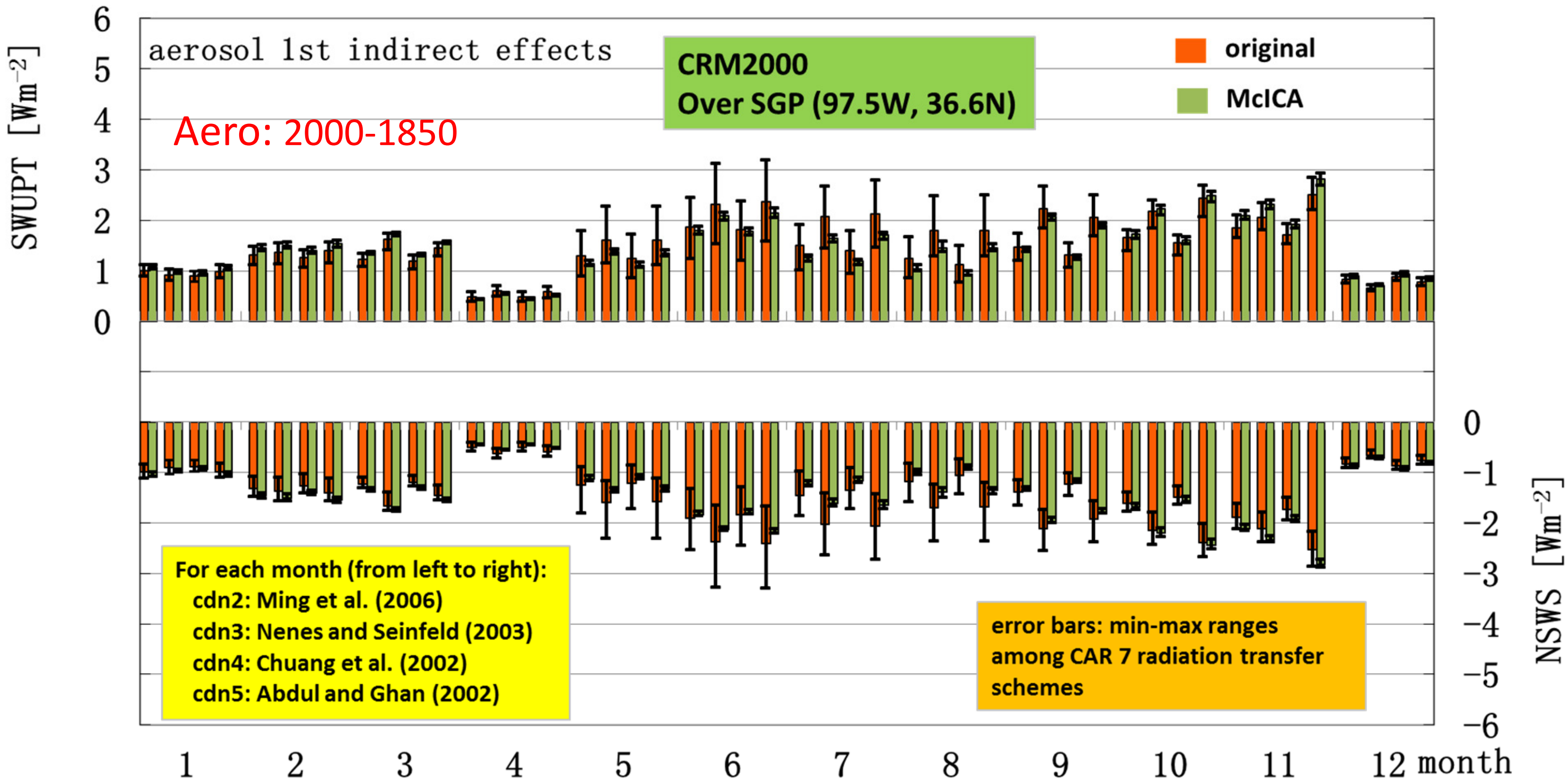
aop3_lw:

Li et al. (2001) and Li and Min 2002 for sulfate and sea salt
Gu et al. (2006) for dust
Baümer et al. (2007) for carbon

aop10_lw:

Li et al. (2001) and Li and Min 2002 for sulfate
Gu et al. (2006) for sea salt and dust
Baümer et al. (2007) for carbon

- Aerosol 1st indirect effects
  - Standalone CAR experiments

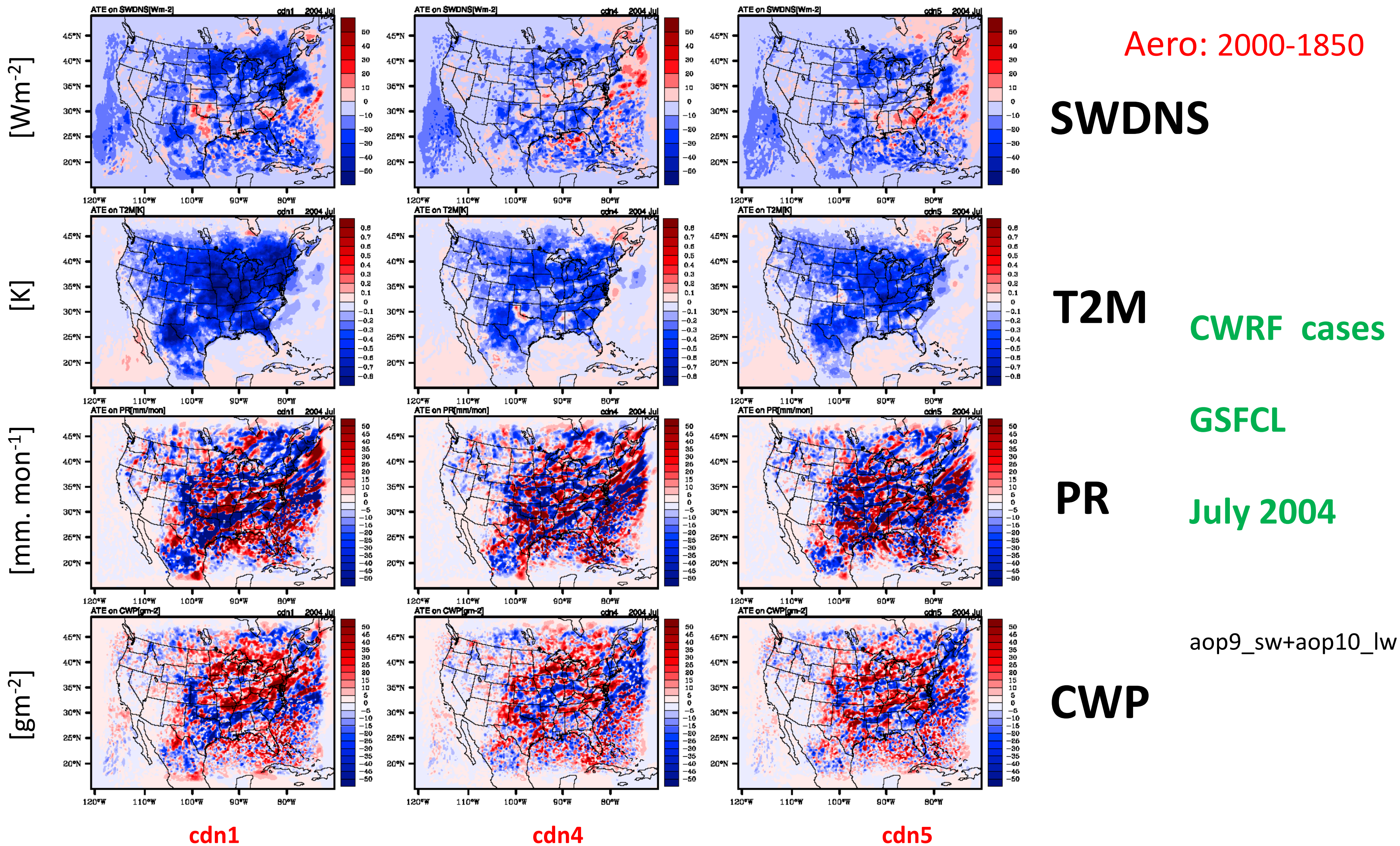


1. The min-max ranges for May ~ Sep. with values about 1.0~1.5 Wm^{-2} from original cloud vertical overlap schemes (red) show the clear differences of aerosol 1^{st} indirect effects among different radiation schemes with different build-in cloud vertical overlap schemes.

2. Strikingly, when McICA treatment is consistently applied to each of radiation code, the min-max range largely decrease, especially by a factor of 8-10 for JJA, indicating that **the same cloud profiles, due to McICA treatments consistently applied, largely reduce the differences of the aerosol 1^{st} indirect effects among different radiation transfer codes. So cloud vertical overlap treatment do play an important influence on aerosol 1^{st} indirect effects.**

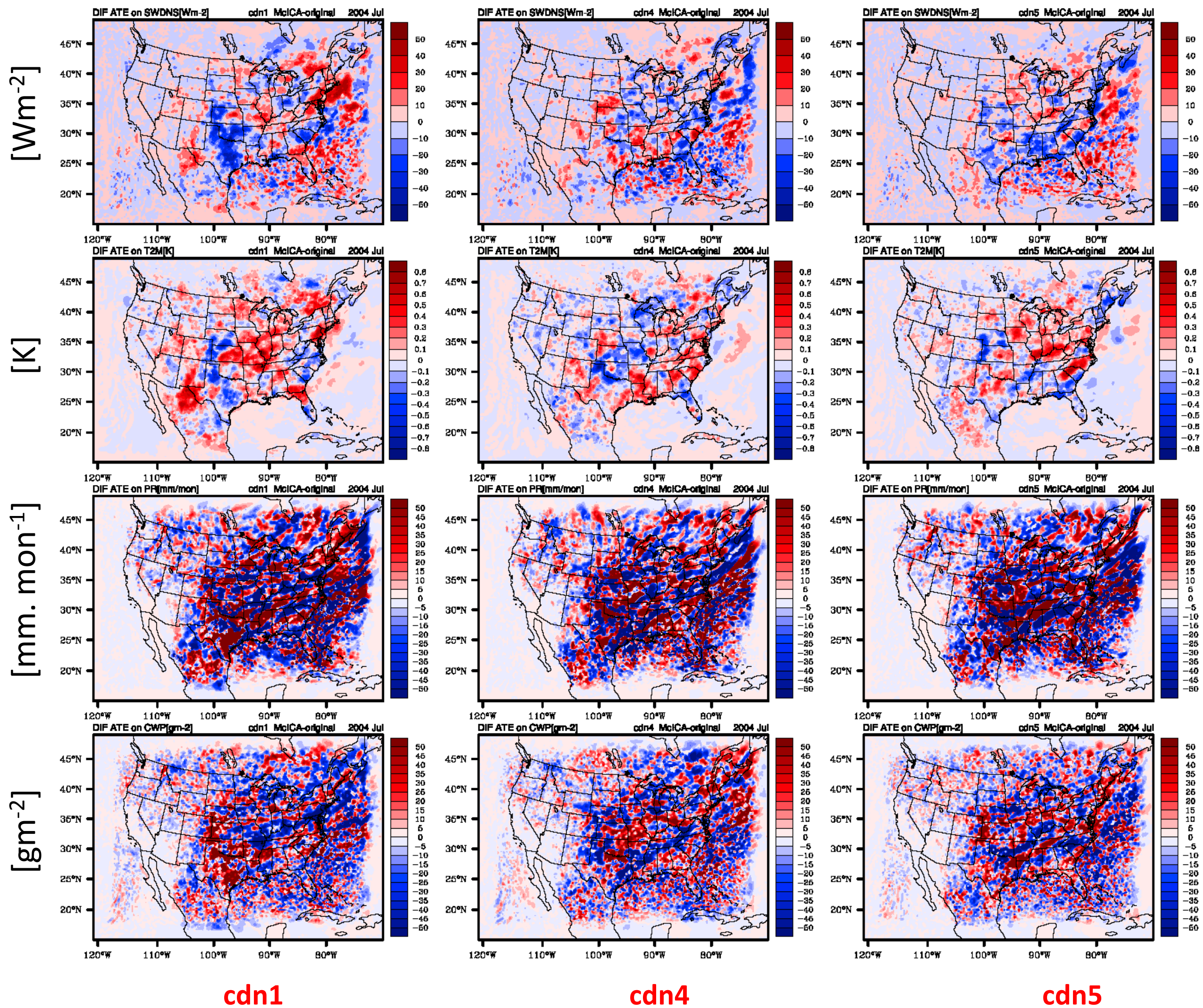
3. Obvious differences exist among different cdn schemes, especially for May to September.

- Aerosol direct + 1st indirect effects
  - CWRF/CAR on-line experiments



Monthly mean **aerosol direct + 1st indirect effects (ATE)** on SWDNS [Wm^{-2}], T2M [K], PR [$mm.month^{-1}$], and CWP [gm^{-2}] for **3 CAR cloud cdn schemes** by using **CMIP5 recommended data** for July 2004, respectively.

Clearly different CAR cdn schemes have different influences on aerosol 1st indirect effects.



McICA - original

Aero: 2000-1850

SWDNS

T2M

CWRF cases

GSFCL

July 2004

PR

CWP

aop9_sw+aop10_lw

The differences of monthly mean **aerosol direct + 1st indirect effects (ATE)** on SWDNS [Wm^{-2}], T2M [K], PR [$mm.month^{-1}$], and CWP [gm^{-2}] **between Mcica treatment and original cloud vertical overlap schemes** for 3 CAR cloud cdn schemes by using **CMIP5 recommended data** for July 2004.

Clearly different cloud vertical overlap treatments have quite different influence on aerosol 1st indirect effects, too.

Conclusions:

Cloud, aerosol, radiation complicatedly interact with each other, which needs further studies, especially for the projection of the future climate changes. In the CAR,

- cloud, aerosol, and radiation transfer have been separated;
- the radiative effects of cloud inlcuding cloud vertical overlap and aerosol including aerosol 1st indirect effects are explicitly treated;
- by using the climate model coupled with the CAR, the comprehensive studies on the different roles of the different cloud/aerosol/radiation factors in cloud-aerosol-radiation interaction and its feedback can be conducted.

CAR system undoubtedly assume powerful applications in further studies on cloud-aerosol-radiation interactions.

By using the CAR system, the following things also can be done:

- To make better intercomparisons among different radiation transfer codes, especially under cloudy sky.
- To explicitly compare the performances of different cloud schemes, such as for cloud cover, for cloud effective radius/size, or for cloud vertical overlap, in different seasons and/or over different regions. The same studies can be done for aerosol part and radiation part.
- To make comprehensive validations of the cloud/aerosol/radiation related representations in current models with observations.
- To study aerosol 2nd indirect effects by using CWRF/CAR.

Thanks a lot!

Some CAR schemes used in this presentation

The system incorporates 7 major radiation transfer schemes:

1.gsfcl (NASA), maximum/random cloud vertical overlap among high/middle/low cloud bulks.

2.cccma (Canada), McICA treatment with random cloud generator 3 (Räisänen et al. 2004 modified by Jason Cole to include the cloud sub-grid variability)

3.cam (NCAR), maximum/random cloud vertical overlap scheme for adjacent and non-adjacent layers

4.flg (popular for DOE/ARM), maximum/random cloud vertical overlap among high/middle/low cloud bulks

5.gfdl (NOAA), McICA treatment with random cloud generator 2 (Räisänen et al. 2004 for inhomogeneous clouds)

6.rrtmg (NCEP, ECMWF, future NCAR), McICA treatment with random cloud generator 1 (Räisänen et al. 2004 for homogeneous clouds)

7.cawcr(Australia), maximum/random cloud vertical overlap scheme for adjacent and non-adjacent layers

McICA cloud treatment is Monte-Carlo Independent Column Approximation (McICA; Barker et al. 2002; Pincus et al. 2003; Räisänen et al. 2004), which is consistently applied to each CAR major radiation transfer scheme.

This approach decouples the determination of cloud structure from the calculation of radiative transfer. Thus the distribution of clouds and optical properties within a model grid column can be more flexibly made and consistently applied to different radiation transfer schemes.

McICA assumes all cloud types to follow the same statistical relationship, e.g., symmetrical β distribution.

Table 2b Schemes for aerosol optical properties (SW)

sulfate	1	Based on relative humidity and look-up tables (Li et al. 2001)
	2	Based on relative humidity and prescribed optical properties (Gu et al. 2006)
	3	Based on prescribed optical properties (Kiehl and Briegleb 1993)
sea salt	1	Based on relative humidity and look-up tables with data from G. Lensins (Li et al. 2001)
	2	Based on relative humidity and prescribed optical properties (Gu et al. 2006)
dust	1	Based on look-up tables with data from G. Lensins (Li et al. 2001).
	2	Based on relative humidity and prescribed optical properties (Gu et al. 2006)
carbon	1	Based on relative humidity for hydrophilic OC and look-up tables computed from the Mie theory (Baümer et al. 2007)
	2	Based on prescribed optical properties (Gu et al. 2006)

Aerosol optical property schemes based on mass loading

Table 2c Schemes for aerosol optical properties (LW)

sulfate	1	Based on relative humidity and look-up tables (Li et al. 2001; Li and Min 2002)
	2	Based on relative humidity and prescribed optical properties (Gu et al. 2006)
sea salt	1	Based on relative humidity and look-up tables with data from G. Lensins (Li et al. 2001; Li and Min 2002)
	2	Based on relative humidity and prescribed optical properties (Gu et al. 2006)
dust	1	Based on look-up tables with data from G. Lensins (Li et al. 2001; Li and Min 2002)
	2	Based on the prescribed optical properties (Gu et al. 2006)
carbon	1	Based on relative humidity for OC and look-up tables computed from the Mie theory (Baümer et al. 2007)

MISR aerosol optical properties

The MISR aerosol data are including angstrom's exponent, the total optical depth and single scattering albedo for 4 spectral bands: blue, green, red, and NIR bands.

In order to get the broad-band mean aerosol optical depth (AOD) used in radiation transfer codes, first the angstrom's exponent is used to get the AOD spectral dependence:

$$\tau(\lambda) = \tau_r \left(\frac{\lambda_r}{\lambda}\right)^{\alpha} \quad \text{(A1)}$$

where, α the angstrom's exponent, λ wavelength, λ_r and τ_r the reference wavelength and optical depth, $\tau(\lambda)$ the optical depth at λ. Here, the MISR green and NIR band values are used as the references for VIS band (0.4-0.7μm) and for NIR band (0.7-1.3μm), respectively. Then, integrating (A1) over spectral band to get the spectral mean values:

$$\tau_{vis} = \int_{0.4}^{0.7} \tau(\lambda) s_\lambda d\lambda \Big/ \int_{0.4}^{0.7} s_\lambda d\lambda, \quad \text{(A2)}$$

$$\tau_{nir} = \int_{0.7}^{1.3} \tau(\lambda) s_\lambda d\lambda \Big/ \int_{0.7}^{1.3} s_\lambda d\lambda \quad \text{(A3)}$$

Where s_λ the insolation at wavelength λ.

For broad-band mean single scattering albedo (SSA), for VIS band, the second order Lagrange polynomial is used to get the SSA spectral dependence of SSA:

$$SSA(\lambda) = l_0(\lambda) SSA_{blue} + l_1(\lambda) SSA_{green} + l_2(\lambda) SSA_{red} \quad \text{(A3)}$$

Where
$$l_0(\lambda) = \frac{(\lambda - \lambda_{green})(\lambda - \lambda_{red})}{(\lambda_{blue} - \lambda_{green})(\lambda_{blue} - \lambda_{red})}$$
$$l_1(\lambda) = \frac{(\lambda - \lambda_{blue})(\lambda - \lambda_{red})}{(\lambda_{green} - \lambda_{blue})(\lambda_{green} - \lambda_{red})} \quad \text{(A4)}$$
$$l_2(\lambda) = \frac{(\lambda - \lambda_{blue})(\lambda - \lambda_{green})}{(\lambda_{red} - \lambda_{blue})(\lambda_{red} - \lambda_{green})}$$

So the VIS broad-band mean SSA is:

$$SSA_{vis} = \frac{\int_{0.4}^{0.7} SSA(\lambda) s_\lambda d\lambda}{\int_{0.4}^{0.7} s_\lambda d\lambda} \quad \text{(A4)}$$

For NIR broad band, the MISR SSA at NIR are directly used.

MISR has no data for asymmetry factor. Here, the MODIS broad-band mean asymmetry data is used.

When the total visible and NIR spectra are not the same with (0.4-0.7μm) and (0.7-1.3μm), the following simple scaling for AOD is applied:

$$\overline{\tau}_{vis} = \tau_{vis} \int_{0.4}^{0.7} s_\lambda d\lambda \Big/ \sum_n \int_{\lambda_{n0}}^{\lambda_{n1}} s_{n\lambda} d\lambda \quad \text{(A5)}$$

$$\overline{\tau}_{nir} = \tau_{nir} \int_{0.7}^{1.3} s_\lambda d\lambda \Big/ \sum_n \int_{\lambda_{n0}}^{\lambda_{n1}} s_{n\lambda} d\lambda \quad \text{(A6)}$$

Where n the number of solar spectrums in (0.4-0.7μm) or (0.7-1.3μm), λ_{n0} and λ_{n1} the lower and upper limits for each spectrum. Clearly after this scaling, the MISR data can be uniformly applied for all CAR radiation schemes.

Due to some missing data for MISR climatological data, accordingly a uniform global flag data (0: without observation data; 1: with observation data) are generated. Only those grids with flag=1 are be analyzed for the offline aerosol experiments (CAR AerExps).

For MODIS data, the processing is similar (not shown).

5 aerosol 1st indirect effect schemes (cloud nucleation schemes)

1. Martin et al. 1994. This scheme is parameterized from the observations of the microphysical characteristics of warm stratocumulus clouds (empirical relationship).

The below 4 schemes (physically based) based on a mechanistic parameterization of nucleation consider the atmospheric chemical reactions (e.g., aqueous phase oxidation of SO_2 followed by by evaporation of the drops) and aerosol activation (An aerosol particle becomes activated as a CCN when the environmental supersaturation ratio becomes greater than its critical value).

2. Ming et al. 2006 (cdn as the function of parcel maximum supersaturation Smax, bisection method)

3. Nenes and Seinfeld 2003 (parcel maximum supersaturation Smax, bisection method)

4. Chuang et al. 2002 (a means is developed for relating the predicted anthropogenic sulfate mass to cloud drop number concentration over the range of expected conditions associated with continental and marine aerosols).

5. Abdul and Ghan 2002 (parcel maximum supersaturation Smax, parameterization)

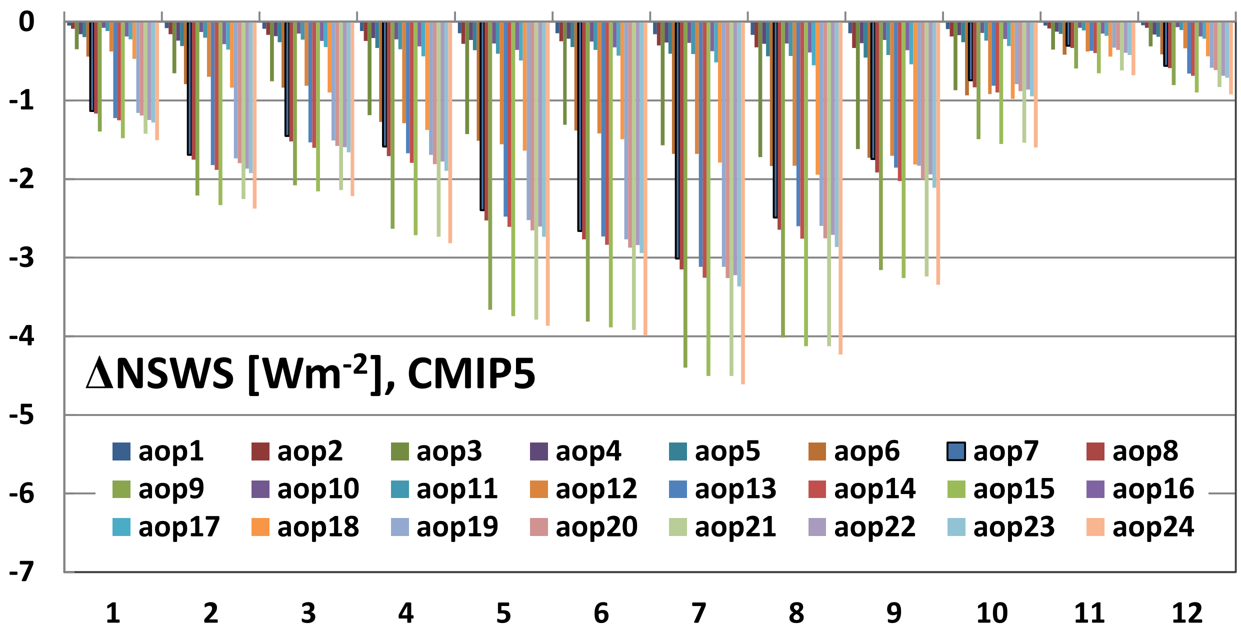


Fig. 6 Monthly mean aerosol direct effects on NSWS by using CMIP5 recommended aerosol mass loading.

The radiation transfer code is GSFCL.

color bars are for 24 CAR-aerosol SW optical scheme combinations.

CRM cases

	sulfate	sea salt	dust	carbon	aerosol effects
aop1	1,0,0	1,0	1,0	1,0	
aop2	0,1,0	1,0	1,0	1,0	these 8 are smallest
aop4	1,0,0	0,1	1,0	1,0	
aop5	0,1,0	0,1	1,0	1,0	
aop10	1,0,0	1,0	1,0	0,1	
aop11	0,1,0	1,0	1,0	0,1	
aop16	1,0,0	0,1	1,0	0,1	
aop17	0,1,0	0,1	1,0	0,1	
aop3	0,0,1	1,0	1,0	1,0	
aop6	0,0,1	0,1	1,0	1,0	
aop12	0,0,1	1,0	1,0	0,1	these 4 are the second smallest
aop18	0,0,1	0,1	1,0	0,1	
aop7	1,0,0	1,0	0,1	1,0	
aop8	0,1,0	1,0	0,1	1,0	
aop13	1,0,0	0,1	0,1	1,0	
aop14	0,1,0	0,1	0,1	1,0	these 8 are the second largest
aop19	1,0,0	1,0	0,1	0,1	
aop20	0,1,0	1,0	0,1	0,1	
aop22	1,0,0	0,1	0,1	0,1	
aop23	0,1,0	0,1	0,1	0,1	
aop9	0,0,1	1,0	0,1	1,0	
aop15	0,0,1	0,1	0,1	1,0	these 4 are the largest
aop21	0,0,1	1,0	0,1	0,1	
aop24	0,0,1	0,1	0,1	0,1	

Table 2a Schemes for aerosol optical properties (SW)

sulfate	1	Based on relative humidity and look-up tables (Li et al. 2001)
	2	Based on relative humidity and prescribed optical properties (Gu et al. 2006)
	3	Based on prescribed optical properties (Kiehl and Briegleb 1993)
sea salt	1	Based on relative humidity and look-up tables with data from G. Lensins (Li et al. 2001)
	2	Based on relative humidity and prescribed optical properties (Gu et al. 2006)
dust	1	Based on look-up tables with data from G. Lensins (Li et al. 2001).
	2	Based on relative humidity and prescribed optical properties (Gu et al. 2006)
carbon	1	Based on relative humidity for hydrophilic OC and look-up tables computed from the Mie theory (Baümer et al. 2007)
	2	Based on prescribed optical properties (Gu et al. 2006)

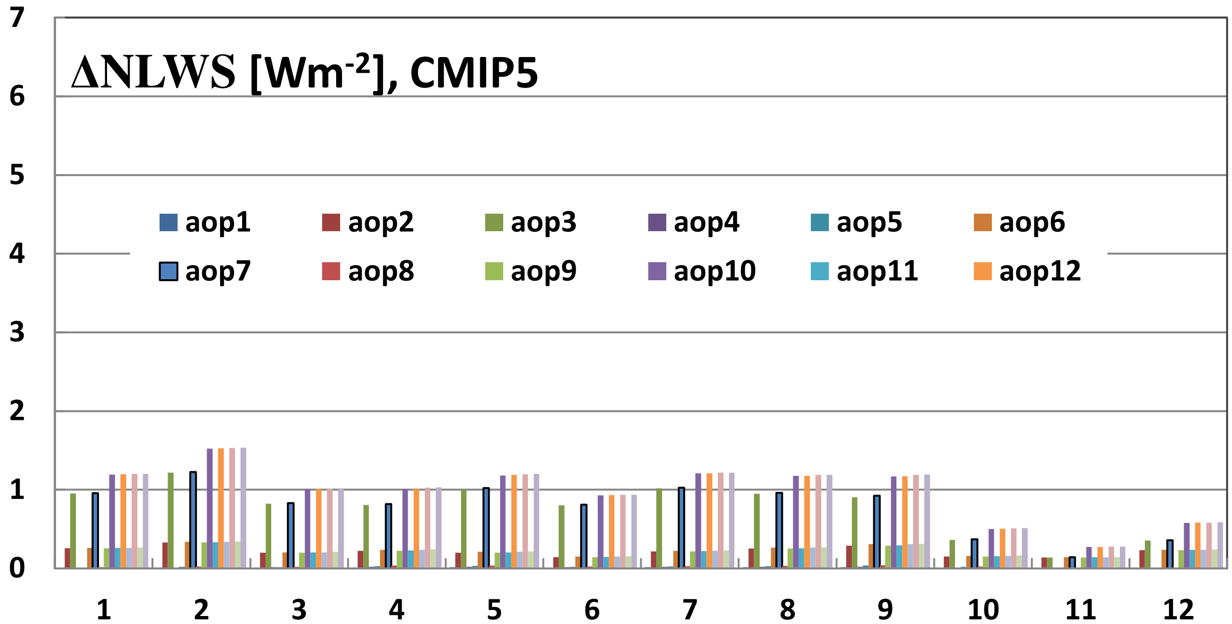


Fig. 7 Monthly mean aerosol direct effects on NLWS by using CMIP5 recommended aerosol mass loading.

The radiation transfer code is GSFCL.

color bars are for 16 CAR-aerosol LW optical scheme combinations.

CRM cases

	sulfate	sea salt	dust	carbon	aerosol effects
aop1	1,0	1,0	1,0	1,0	
aop4	1,0	1,0	1,0	0,1	these 4 are smallest.
aop5	0,1	1,0	1,0	1,0	
aop8	0,1	1,0	1,0	0,1	
aop2	1,0	0,1	1,0	1,0	
aop6	0,1	0,1	1,0	1,0	
aop9	1,0	0,1	1,0	1,0	these 6 are the second smallest.
aop11	1,0	0,1	1,0	0,1	
aop13	0,1	0,1	1,0	1,0	
aop15	0,1	0,1	1,0	0,1	
aop3	1,0	1,0	0,1	1,0	these 2 are the second largest.
aop7	0,1	1,0	0,1	1,0	
aop10	1,0	0,1	0,1	1,0	
aop12	1,0	0,1	0,1	0,1	these 4 are the largest.
aop14	0,1	0,1	0,1	1,0	
aop16	0,1	0,1	0,1	0,1	

Table 2b Schemes for aerosol optical properties (LW)

sulfate	1	Based on relative humidity and look-up tables (Li et al. 2001; Li and Min 2002)
	2	Based on relative humidity and prescribed optical properties (Gu et al. 2006)
sea salt	1	Based on relative humidity and look-up tables with data from G. Lensins (Li et al. 2001; Li and Min 2002)
	2	Based on relative humidity and prescribed optical properties (Gu et al. 2006)
dust	1	Based on look-up tables with data from G. Lensins (Li et al. 2001; Li and Min 2002)
	2	Based on the prescribed optical properties (Gu et al. 2006)
carbon	1	Based on relative humidity for OC and look-up tables computed from the Mie theory (Baümer et al. 2007)
	2	Based on the prescribed optical properties (Gu et al. 2006)